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ON THE COOLING OF MICROWAVE DETECTORS

by
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ON THE COOLING OF MICROWAVE DETECTORS

I INTRODUCTION

As increasing emphasis in the field of microwave electronics is placed upon systems designed for communication between space vehicles, and upon systems for radio astronomy observations to be made from vehicles located outside the earth's atmosphere, the need for better detectors of microwave energy, especially at the millimeter and submillimeter wavelengths, becomes more apparent.

Basically, two main types of detectors are at present being widely used at microwave frequencies: a) those which rectify (including mixing) the E field of the incident radiation and provide a voltage output; and b) those which measure the heating effects of the microwave radiation upon the physical properties of some material. In both types of detectors noise is introduced by the detector itself. In many instances this noise is much less than the incident signal (or the noise accompanying the signal) into the detector, and is therefore of little consequence. However, in space communications or radio astronomy, the signals to be detected and the background noise associated with the signals are of such small magnitude that the noise introduced by the detection system will be of great consequence. In many cases it is the limiting factor in the design of an operating system. Fig. 1 shows the relative sensitivity and the operating frequency range of the various detectors.

Much of the noise in the conventional detection system is thermally-generated and is extremely temperature-dependent, increasing with increasing temperature. Thus, by cooling a conventional detection system utilizing crystals or bolometers one might expect to reduce its noise figure considerably. As we shall see later, this turns out to be untrue for many detectors, while in some other cases a definite reduction in the noise level can be obtained.

In this technical note a general discussion of the reduction of detector noise via the thermal cooling method is given from both the theoretical and the experimental points of view. All experimental data are obtained from the previously published results of other researchers and from our own experiments.

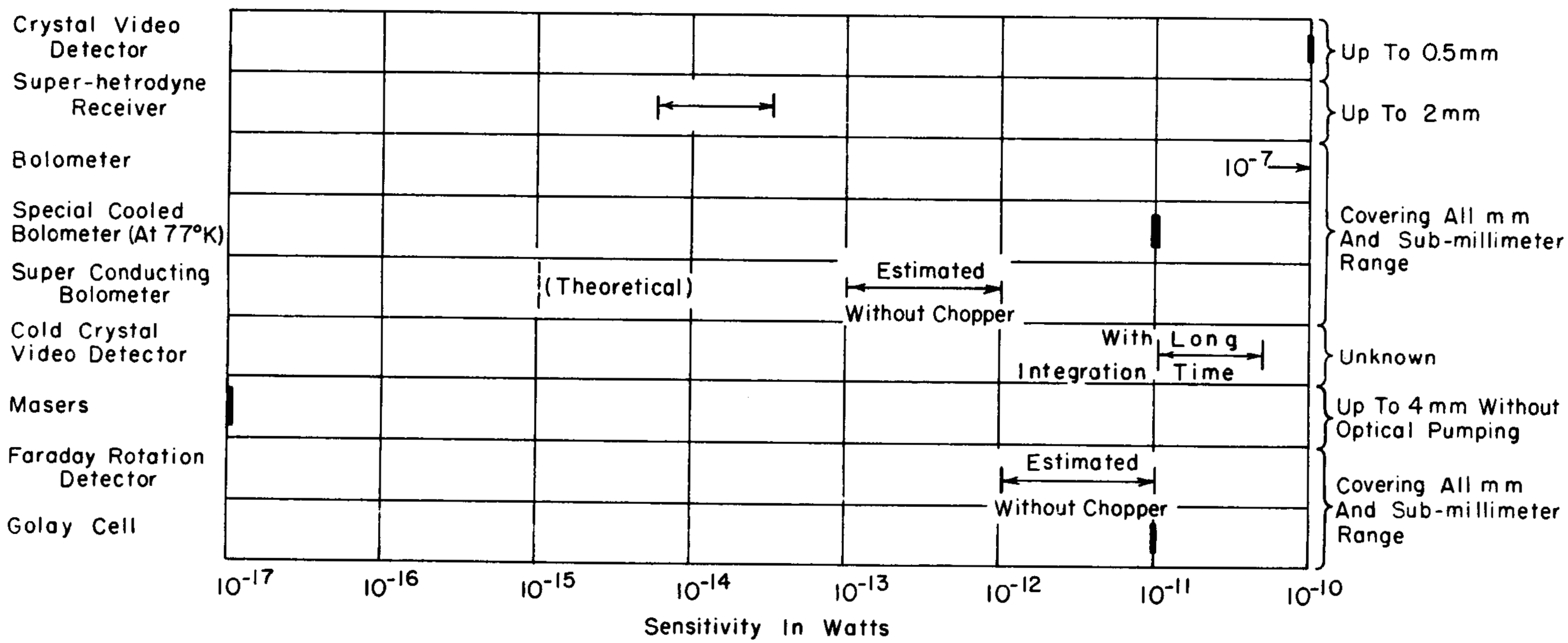

Fig. 1. Sensitivity of Various Microwave Detectors.

II NOISE REDUCTION EFFECTED BY THE COOLING OF MICROWAVE DIODES

Much of the noise generated by a semiconductor diode is known to be temperature dependent, and it can accordingly be reduced by the cooling of the diode. However, such cooling will simultaneously change other parameters of the diode in such a way as to degrade its performance as a video detector or superheterodyne mixer at microwave frequencies. One of the factors which must be considered is the decrease in the concentration of thermally-excited carriers as the temperature is lowered. This precludes the use of silicon diodes at very low temperatures and necessitates the use of germanium or indium diodes instead. This and other factors will be discussed under two main classifications of diode microwave application: as video detectors, and as superheterodyne mixers.

1. The Theoretical Analysis of Cold Diodes

a) Microwave Diodes as Video Detectors

The voltage signal-to-noise ratio of a video detector is given by [1] :

$$\frac{E}{N} = \frac{\beta\, PR}{\sqrt{4k\, TB\ (R + R_A)}} \tag{1}$$

where:

β is the current sensitivity of the detector in amp. per watt
P is the incident power
R is the video resistance of the diode as measured with a very small voltage applied ($\approx$ 5mv) in either the forward or reverse direction
k is Boltzmann's constant
B is the bandwidth in cycles
R_A is the equivalent noise resistance of the amplifier following the video detector, usually standardized at 1200 ohms.

The quantity $\frac{\beta\, R}{\sqrt{R + R_A}}$ = M is the "figure of merit" of the video detector and is usually in the vicinity of 70, although it may be as low as 50 or as high as 200.

At room temperature the crystal video resistance is approximately 5,000 ohms.

As shown in the above equations, the noise in a video detector comes primarily from thermal noise in the video resistance, provided that the detector is operated at low power levels. The noise-equivalent sensitivity of the video detector is found by assuming the signal-to-noise ratio to be 1.0 and solving for P. Then:

$$P_{min} = \frac{\sqrt{4k\ TB\ (R + R_A)}}{\beta\ R} \approx \frac{1}{\beta} \sqrt{\frac{4k\ TB}{R}} \qquad (2)$$

which indicates that P_{min} is approximately proportional to $\sqrt{T}/\sqrt{R}$. Since R increases as T is decreased, we would expect P_{min} to decrease as the temperature of the crystal is lowered (an increase in the noise-equivalent sensitivity).

The above reasoning may be carried only to a certain limit, since the approximate relation given in (2) depends upon the video resistance being much smaller than the input impedance of the following amplifier stage. It should also be noted that the sensitivity is dependent upon the bandwidth of the video signal, being greatest for an extremely narrow bandwidth. For values[2] such as $T = 293^{o}K$, $M = 70$, $R = 5{,}000$ ohms, $R_A = 1200$ ohms, $P_{min} \approx 1.8 \times 10^{-12}\sqrt{B}$ watts; or $P_{min} \approx 1.8 \cdot 10^{-9}$ watts for a 1 Mc bandwidth. From the theoretical point of view presented above, decreasing temperature of the diode to that of liquid nitrogen should give a 2-3 db reduction in P_{min}.

b) Microwave Mixer Diodes

The noise in a mixer diode is of a more complicated origin than the noise in a video diode; this is due to the presence of other parameters which have a bearing on the noise figure of the diode: d-c bias, local-oscillator power, and conversion loss. These several factors must be considered simultaneously.

The relative noise temperature of a superheterodyne receiver is given by [3,4]:

$$\tau_{rec} = \frac{T_{rec}}{290^{o}K} = (F_x - 2) + L_x (F_{if} - 1) + 2\tau_i \qquad (3)$$

for a "broadband" receiver (no image rejection), or

$$\tau_{rec} = \frac{T_{rec}}{290^{o}K} = (F_x - 1) + L_x (F_{if} - 1) + \tau_i \qquad (4)$$

for a receiver having image-rejection, where:

F_x = mixer noise figure

F_{if} = intermediate-frequency amplifier noise figure

L_x = conversion loss, the ratio of input signal power to the power output at the IF frequency

τ_i = relative noise temperature of the antenna or transmission system to which the detector is connected.

In general, F_x and L_x will depend upon the operating temperature of the mixer diode and the frequency at which it is being operated.

In the following discussion, we will consider a broad-band receiver. The conversion or mixing action is due to the interaction of the local oscillator and the signal voltages with the nonlinear barrier resistance of the diode junction. For small signal levels an IF output is produced whose power is approximately proportional to $1/L_x$ times the input signal power.

The broad-band mixer circuit may be thought of as a passive three-port network with one port for the signal, a second for the image, and a third for the IF output.

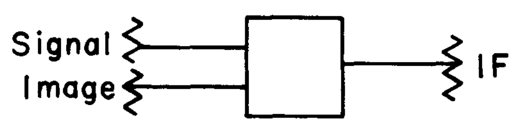

Fig. 2. Diagramatic Representation of a Mixer Circuit.

If all three ports are matched to their loads, and if the network is lossless, half of the signal power will be dissipated in the IF load, and half in the image load. Thus, for a "broadband" mixer, L_x may never be less than two (nor less than one for a "narrowband" mixer where the image is rejected). At room temperature, L_x is in the neighborhood of three or four for a practical mixer. L_x is usually measured by the incremental method by varying the local oscillator power over a given increment. In this case,

$$L_x = \frac{(\Delta P)^2}{(\Delta I)^2 \; 2P \, R_L} \tag{5}$$

where:

P = average power level of signal

ΔI = change in the crystal current caused by a change in P

R_L = load resistance of crystal.

The conversion loss will decrease somewhat as the local-oscillator power is increased, but the additional noise due to the excess local-oscillator power in the spreading resistance and the barrier capacitance negates any improvement which might be obtained by increasing the local-oscillator power past the proper level.

The important noise sources in the mixer are: a) thermal noise in the spreading resistance around the small contact point, b) barrier noise due to the rectification action, and c) fluctuations due to the surface ions on the semiconductor or caused by the fluctuations of the semiconductor-to-metal contact at the catwhisker point. The thermal noise and barrier noise are almost proportional to the local-oscillator power level; while the fluctuation noise has a 1/f spectrum and is not very great above 500 kc at room temperature.

Since the noise figure of the mixer is dependent upon both the noise temperature ratio and the conversion loss, the quantity $(F_x - 2) = (L_x t_x - 2)$ may be approximately written[4] as $\bar{t} \doteq (L_x - 2)$. If the local-oscillator drive is small, $\bar{t} < 1.5$; and with a good 30-Mc IF amplifier, $L_x(F_{if} - 1)T_o$ (where $T_o = 293^oK$) can be kept within the range of approximately 20^oK. Thus, the over-all noise temperature of a good broadband receiver can be kept within $[\tau_{rec}] \times 290^oK \doteq [2 \times 290^o] + 20^o \approx 600^oK$.

In a semiconductor diode,

$$I = A e^{\phi_o/kT} [e^{qV/kT} - 1] \qquad (6)$$

and

$$\frac{dI}{dV} = I_S \left(\frac{q}{kT}\right) e^{qV/kT} \qquad (7)$$

where q = electronic charge. Thus, as T is decreased, $\frac{dI}{dV}$ is increased and it is therefore possible to obtain efficient conversion action at lower levels of local-oscillator power by cooling the diode. Since the barrier and thermal noise sources decrease with decrease in the power level of the local-oscillator signal, this permits a reduction in the noise level from these sources. However, this can be carried out only to a certain extent, since I_S depends upon the concentration and mobility of the carriers, and lowering T to too great an extent causes the carrier concentration to decrease below the amount necessary for efficient diode action. This effect is more prevalent in silicon than in germanium, and therefore we would expect that a germanium diode would be more suitable for use at extremely low temperatures.

Much of the fluctuation noise in a mixer diode (sometimes called the 1/f noise) originates in the so-called parasitic elements, C_b, the barrier capacitance, and R_S, the spreading resistance.[4] The product $R_S\, C_b$ is proportional to:

$$a\left[\frac{\epsilon^{\frac{1}{2}}}{N^{\frac{1}{2}} \cdot b}\right] = \frac{a}{b}\sqrt{\frac{\epsilon}{N}} \qquad (8)$$

where:

ϵ = dielectric constant
N = carrier concentration
a = radius of the catwhisker contact
b = carrier mobility.

ϵ, N, and b are dependent upon the type of material being used, and N and b upon the temperature. The use of germanium instead of silicon as the semiconductor element gives a reduction of 2.5 times in the $C_b R_S$ product.

From the above, it would appear that we could reduce the noise level of a superheterodyne receiver by using a germanium mixer diode cooled to a low temperature of $\approx 75^oK$. McCoy[4] has calculated that cooling to 70^oK may give a 0.6 db decrease in the noise level of a superheterodyne receiver (where $F_{if} = 1.3$) over the noise level at room temperature.

2. Comparison of Theory and Experimental Results Concerning the Cooling of Microwave Diodes

Thus far, the experimental work done on the cooling of microwave diodes has shown that the improvement obtained by cooling the diodes has not been as great as expected, and in many cases the performance of the diode was degraded or the diode was destroyed when subjected to cooling.

A number of investigations have been conducted by various researchers into the effects of cooling commercially available microwave diodes. Messenger[3] conducted some tests in a broad-band superheterodyne receiver at X-band frequency on six 1N263 mixer crystals cooled to 220°K, and was able to attain a maximum in the receiver noise figure of about 0.7 db for one of the diodes tested. The rest of the diodes had a reduction in noise figure of between 0.25 and about 0.6 db at 220°K as compared with 300°K. Tests at temperature lower than 220°K were not attempted by Messenger.

Anderson and Hendry [5] extended the cooling range down to the temperature of liquid nitrogen, also using 1N263 diodes and conducting the tests at 9375 Mc Twelve diodes tested at room temperature and liquid-nitrogen temperature showed no consistent improvement at the lower temperature. Ten of the diodes showed an increase in noise figure of between 0.1 and 4.0 db, while only two diodes showed decreases of 0.1 and 0.6 db, respectively, when operated at liquid-nitrogen temperature. Two crystals were checked at 20° intervals from room temperature down to liquid-nitrogen temperature with the following results: a) the conversion loss decreased as the temperature was lowered, by about 0.45 db at 73°K for one diode, and by about 0.24 db at 133°K for the other. In the case of the latter the conversion loss again increased slightly as the temperature was lowered from 133°K to 73°K; b) the noise factor of one diode decreased about 0.17 db on cooling to 170°K, and the noise factor of the second decreased by about 0.14 db on cooling to 210°K Both diodes had much higher noise factors at liquid-nitrogen temperature than at room temperature; c) the crystal IF resistance increased linearly as the temperature was decreased from about 105 ohms at room temperature to about 150 ohms at liquid-nitrogen temperature for both crystals; d) during the measurements it was noted that the conversion loss and IF resistance varied erratically as the crystal was warmed or cooled. This could be due to mechanical movement of the catwhisker on the silicon chip. Further tests indicated that the noise-temperature ratio of some of the diodes tested could be lowered by about 0.3 to 0.6 db by operating them at -75°C, but that this advantage was offset by the disadvantage of having erratically varying crystal parameters at this temperature. Out of the seventeen diodes tested, two were ruined by the temperature cycling and others showed minor cracks and broken lead seals.

From the information obtained by Messenger and by Anderson and Hendry, we may conclude that the cooling of 1N263 X-band diodes to liquid-nitrogen temperature is entirely impractical since the noise level is higher at that temperature than at room temperature. Also, although both experimenters noted that some improvement could be obtained by cooling the diodes to the vicinity of 200°K, the fluctuations in the crystal parameters at this temperature and the resultant loss in reliability offset the small improvement in noise figure thus obtained.

The subject of erratic fluctuations in the parameters of microwave diodes due to cooling was also mentioned by Ginzton [6]. He states that it was observed that diodes in which a wax filler was used for mechanical stabilization of the catwhisker seemed to be worse in this respect than those in which a filler is not used. Apparently, the fluctuations (and sometimes the complete failure) of the diode were due to mechanical movement or stresses associated with the catwhisker-crystal contact. If this is the case, then diodes in which the contact area is small and the pressure of the catwhisker against the crystal is very light should be more susceptible to trouble than the more ruggedly constructed low-frequency diodes This was confirmed by tests in this laboratory.

A preliminary investigation was performed on two 1N23B diodes by enclosing a diode in a brass container of considerable mass which was lowered into a liquid nitrogen bath. The mass of the container required several minutes to permit the diode to cool from room temperature to the approximate temperature of liquid nitrogen. A qualitative indication of the forward resistance of the diode was obtained by the use of the RX100 scale of a Simpson Model 260 multimeter. During the slow cooling of the diode the forward resistance fluctuated quite widely, although in general it was lower during the cooling process than at room temperature or after stabilization at the liquid nitrogen temperature. During warming to room temperature (assisted by the heat from a small acetylene torch) wide resistance fluctuations were again noted, although this time the resistance was, in general, higher than either at low-temperature stabilization or at room-temperature stabilization.

The above-observed shifts in the diode resistances during warming and cooling could possibly be explained as follows: during cooling, the outside of the crystal case is at a lower temperature than the catwhisker and the resulting difference in the expansion of the case and the catwhisker could increase the pressure of the catwhisker upon the silicon chip, thereby causing a decrease in the forward resistance of the diode. During warming the opposite conditions would exist; the diode case would be warmer than the catwhisker, the junction pressure would be less, and the junction resistance would increase.

Following these initial tests a more elaborate means of determining the V-I characteristics of the diode were constructed and four more diodes tested (two 1N21B's and two 1N23B's, both of Sylvania manufacture). The copper vessel used previously was again used and the temperature, forward voltage and current, and reverse voltage and current, were recorded as functions of time. Each diode was subjected to one complete slow cooling and slow warming cycle requiring about 35 minutes for completion, and to three fast cooling and warming cycles, each requiring about 2 minutes for completion. During the slow cooling and warming of the 1N21B diodes no fluctuations or irregularities in either the forward or reverse characteristics could be noted. Both the forward and the inverse currents decreased considerably during the cooling, the reverse current being so small that it could not be read (< 0.50 μa) at temperatures below -150°C. One diode had a forward current of 25.2 ma at 0.70 volts at room temperature, and this dropped to about 10 ma at -150°C and to 2.6 ma at liquid-nitrogen temperature. The corresponding figures for the second 1N21B diode were 43.0, 20, and 5.5 ma, this diode exhibiting somewhat higher conduction in both the forward and reverse directions than the first diode. Both diodes showed no observable fluctuations or irregularities during three cycles of rapid cooling and warming.

Two 1N23B diodes were subjected to the same test and both began to show irregularities (current fluctuations and opens) after the temperature dropped below -50°C. Even after stabilization at liquid-nitrogen temperature, current fluctuations were observed in one diode. The diodes were returned to room temperature and subjected to three rapid cooling and warming cycles. The fluctuations in the current were so large as to make numerical data completely unmeaningful.

Since the 1N23B is an X-band diode designed for higher-frequency operation than the S-band 1N21B, and since the 1N23B therefore has a smaller contact area and contact pressure between the silicon chip and the metal catwhisker, we therefore would believe that the 1N23B would be more subject to fluctuations in its parameters caused by cooling than would the lower-frequency 1N21B. Furthermore, we postulate that the increase in noise figure in the 1N263 diodes as they are cooled below the vicinity of 200°K might be due to mechanical instability of the contact between the catwhisker and the silicon chip. This is substantiated to some extent by the work done on S-band crystals at low temperatures.[13] Based upon the preceding reasoning it is expected that the cooling of crystals for millimeter or submillimeter-wavelength bands would, because of the delicate contact existing between the semiconductor chip and the catwhiskers, cause even more trouble than that observed with the 1N263 and 1N23B X-band crystals.

Moreover, it may be concluded that the cooling of commercially-available microwave diodes at X-band frequencies and higher is a completely unsatisfactory method of obtaining noise reduction consistent with reliability and stable operation. Furthermore, present commercial mixer diodes used in an application where they might inadvertently be subjected to very low temperatures such as on a space platform, should be protected in some manner from actually being exposed to such temperatures.

In the preceding discussion the cooling of commercially available microwave diodes has been considered. Although results have been reported for some work on the development of low-frequency (S-band) microwave crystals suitable for cooling, and on the development of sensitive room-temperature millimeter and submillimeter crystals, the development of a millimeter or submillimeter crystal suitable for cooling is unreported.

G.S. Heller[14] states that in the 2-mm region uncooled crystal detectors formed from 1N26 crystal blanks and gold-plated electrolytically-pointed catwhiskers seem to be as sensitive as a Golay cell at the same frequency (5×10^{-11} watt).

Texas Instruments has reported on the development of an indium antimonide microwave crystal for low-temperature use.[13] In a type of crystal using a tungsten-wire catwhisker welded to the semiconductor chip, exposure to liquid-nitrogen temperature would cause the catwhisker to contract and break away a portion of the chip. A gold wire catwhisker was then tried, but it was found that this type of diode would become shorted or would have a very low breakdown voltage after a short period of use. An alloyed-junction type of diode was tried and found to have very good d-c characteristics, but the barrier-layer capacitance was too great (8 $\mu\mu$f) for good microwave efficiency. A mechanically-stable diode with sufficiently low barrier capacitance for good S-band efficiency was created by forming the bond between the zinc-doped gold catwhisker and the indium-antimonide chip at liquid-nitrogen temperature. Texas Instruments believes that it may be possible to develop indium antimonide diodes for low-temperature mm-wavelength use which are comparable with silicon diodes at the lower microwave frequencies. At 3 Kmc they have observed noise figures as low as 8.8 db for the indium-antimonide diode, which compares favorably with a 7.5-db noise figure for a good silicon diode at the same frequency.

But none of these detectors are expected to provide a substantially more sensitive receiver than the present receivers operated at the long millimeter wavelength region. The only alternative way to obtain a very sensitive receiver is to use a low noise preamplifier such as the parametric amplifier or the maser.

It is interesting to note at this point that Bell Laboratories recently reported [7] that by cooling a diffused mesa-junction germanium varactor diode to 87°K, they were able to reduce its excess noise temperature from 150°K to 44°K while operating with a gain of 13 db and a bandwidth of 25 Mc at 6 kmc. It should be noted that this is an amplifying device and not a video detector or mixer diode, and that no such diodes are available at present for use at millimeter wavelengths.

3. Conclusions Regarding the Cooling of Microwave Diodes

It has been shown that it should be possible from a theoretical point of view to obtain a 2-3 db reduction in the noise level of a video-detector diode, and about 0.6 db reduction in the noise level of a practical broadband superheterodyne receiver by cooling the semiconductor diode to a low temperature. However, the experimental results obtained by a number of experimenters leave serious doubt as to the validity of these theoretical predictions. Although it may be possible to obtain a noise reduction by cooling if the diode to be used is carefully selected, there is still the possibility of the low temperature causing fluctuations in the parameters of the diode, the over-all effects of which may completely negate any desirable effects obtained from the small reduction in the noise level.

In our experiments with the 1N21B and 1N23B crystals we noted that the 1N23B type showed considerably greater irregularities due to cooling than did the 1N21B type. Both crystal types were made by the same manufacturer and were of the same mechanical construction, but were intended for different frequency band applications. For the high-frequency type the barrier capacitance C_b must be lower, and therefore the contact area must be smaller than for the lower-frequency type. Such a diode might be more subject to irregularities due to cooling than would a diode intended for low-frequency use and having a heavier contact pressure. This sort of reasoning can be extended to the diode detectors and mixers at the millimeter wavelengths, where the catwhisker is sharpend to a very fine and delicate point and where the pressure of the contact between the catwhisker and semiconductor chip is quite low.

Based upon the above reasoning, it is concluded that at the present time the cooling of point-contact diodes used as video detectors or mixers at the millimeter wavelengths is a completely unsatisfactory method of reducing the noise level in a millimeter-wave receiver. If another type of detector or mixer diode which does not have a delicate point contact could be constructed for use at these wavelengths, this should not be construed to mean that a reduction in the noise level as predicted in theory could not be satisfactorily obtained with this type of diode by cooling to low temperatures. On the other hand, even if the theoretical reduction in noise figure has been obtained, the amount of noise reduction obtained in this fashion would be much smaller than that offered by using a maser or a parametric amplifier as a pre-amplifier.

From another point of view, since the radiometer mounted on a space platform may encounter low temperatures, one should take precautions to avoid any erratic behavior that this might cause in the receiver due to the effects of low temperature upon the receiver diode.

III BOLOMETERS AT LOW TEMPERATURES

The term "bolometer" encompasses a wide range of detector elements in which electromagnetic radiation incident upon the detector increases its temperature and causes a change in its physical characteristics which are then measured by appropriate means. In general, electrical-resistance bolometers may be divided into two categories: those in which the temperature coefficient of resistance is positive, and those in which it is negative. The former usually have a metal for the sensitive element and are often called "barreters", while the latter usually use a semiconductor, such as a germanium thermistor, for the sensitive element. Both types are used in the infrared and microwave regions. However, other types of bolometers may also be devised, making use of temperature-caused capacitance or indutance changes in an element. Hanel[11] has proposed a dielectric bolometer utilizing the change in capacitance of an element with a change in temperature as the sensitive mechanism.

In this Technical Note the effect of cooling upon the thermistor-type bolometer and upon the barreter-type bolometer for low-temperature operation is considered.

1. Metallic-Element Bolometers

A number of different materials and methods of construction have been employed in metallic bolometers used at infrared and microwave wavelengths, the most common microwave type consisting of a very thin platinum (Wollaston) wire enclosed within a protective plastic housing and mounted in a waveguide parallel to the E-field. Such a bolometer element usually has a thermal time constant of about 1 msec. This limits the use of this type of bolometer to cases where the modulation on the signal is less than about 1 kc. Other types of bolometer which have been used include thin films deposited on a dielectric substrate, and coils of wires or loops of foil placed in the radiation field. All of these elements must be operated in some type of d-c or a-c detection circuit which can measure or detect changes in the bolometer's resistance.

The noise in a bolometer element comes from several sources: a) the thermally-generated noise in the bolometer resistance with an available noise power of 4k TB where k is the Boltzmann constant, T the operating temperature, and B the bandwidth of the detection circuit; b) thermal fluctuation noise which appears as random variations in the resistance of the bolometer element due to fluctuations in the ambient temperature of the bolometer surroundings; c) contact noise generated at the connections between various parts of the bolometer circuit; and d) noise introduced by the circuit used to detect the changes in the bolometer resistance or to supply a bias current through it.

Cooling of the bolometer element should reduce the thermal noise contribution, and controlled cooling should reduce the noise arising from temperature fluctuations of the surroundings. In some tests with a Narda 610B bolometer, we found that the noise-equivalent sensitivity could be increased by 1.5 db by cooling the bolometer to liquid-nitrogen temperature, and Mal'nev and Kremenchugskii[12] were able to obtain an increase in sensitivity of about 14 db at infrared wavelengths by cooling a nickel-foil bolometer to liquid-nitrogen temperatures. They were able to obtain a d-c sensitivity of 1.6×10^{-11} watt using a bolometer element of $0.5\ cm^2$ area with a time constant of 15 seconds.

Still another type of low-temperature metallic bolometer consists of a film or wire of superconducting material operated at a temperature within the transition region between the normal and the superconducting states. Within this region the bolometer resistance changes very rapidly with temperature so that the value of $\frac{\partial V}{\partial T}$ is much greater for a superconducting bolometer than for a conventional metallic bolometer. This means that for a given temperature rise (due to the action of an incident radiation field), the superconducting bolometer will produce a considerably larger voltage output than will the conventional bolometer. The presence of a large value of $\frac{\partial V}{\partial T}$ also makes it possible, by using the heating effects of small bias currents through the bolometer element, to partially cancel out the effects of the conduction of heat away from the bolometer element through its leads and supports. However, the superconducting bolometer has the disadvantage that its zero-signal temperature must be kept within the superconducting transition region (usually 0.02 to 0.05^{o}K wide). The superconducting bolometer will be discussed in more detail in a forthcoming report [15]. Its sensitivity has been estimated to be approximately 10^{-12} to 10^{-13} watt. Theoretically its sensitivity has been estimated to be 10^{-15} watt.

The sensitivity of any bolometer is greatly dependent upon a number of factors: the value of α (the absolute temperature coefficient of resistance of the material), the bias current through the bolometer, the bolometer resistance, the thermal resistance between the bolometer and its surroundings, the temperature fluctuations of the surroundings, whether or not the input signal is chopped, and the sensitivity of the circuit used to detect changes in the bolometer resistance.

2. Bolometers having a Negative Temperature Coefficient of Resistivity

Another type of bolometer element is that which utilizes a material whose resistance increases with a decrease in temperature. The semiconducting thermistor is one such element and is usable for detecting power down to about 10^{-6} watt at room temperature [9].

In a semiconductor material the relative temperature coefficient $\frac{1}{R}\frac{dR}{dT}$ is proportional to $\left(-\frac{\Delta \varepsilon}{k\,T^2}\right)$. Thus, as the temperature is lowered, the resistance of the thermistor becomes very large, but moreover the magnitude of the relative rate of increase of the thermistor resistance becomes larger as the temperature is lowered. This suggests that the sensitivity of a bolometer using a thermistor element might be improved by operation at low temperatures. One difficulty exists in that the resistance of the bolometer becomes extremely large at low temperatures, necessitating a greater effort in reducing the noise level of the detection circuit used to measure the resistance change of the thermistor bolometer than is necessary with the metallic bolometers whose resistance is usually quite low at low temperatures. Another disadvantage of the semiconductor-type bolometer is that a considerable amount of contact noise generally is present, similar to the barrier-layer-generated noise in a solid-state rectifier.

Bogle and Rodgers[10] have reported on a low-temperature bolometer element made from a portion of a carbon radio resistor (a 0.019 inch slice from a 56-ohm resistor). This material behaves like a semiconductor at low temperatures. Although the noise-limited sensitivity of this device was only about 10^{-7} w, there is a possibility of increasing the sensitivity by lowering the noise level. These authors report that indium-amalgam contacts gave the lowest noise level in their experiments.

It is believed that the experimental data presently available on the cooling of metallic bolometers indicates that this would be a fruitful field for further research. Specifically, an investigation of the ultimate sensitivity obtainable with both conventional and superconducting bolometers should be carried out, and the most succesful of these two types then used to construct a sensitive detector for the millimeter* and submillimeter wavelengths.

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*The need for the use of bolometers at the millimeter wavelengths is not very great because the conventional superheterodyne receiver would give a better sensitivity as long as local oscillators and mixers are available.

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